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EFFECTS OF IODINATION ON THE ELECTRICAL CONDUCTIVITY OF  
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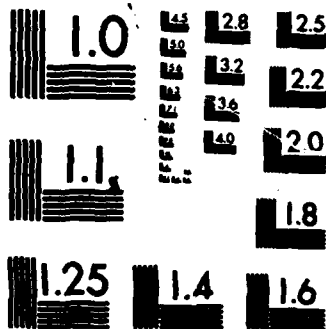
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EFFECTS OF IODINATION ON THE ELECTRICAL CONDUCTIVITY

OF HYDROGEN BIS(PHTHALOCYANINATO) NEODYMIUM(III)

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EFFECTS OF IODINATION ON THE ELECTRICAL CONDUCTIVITY  
OF HYDROGEN BIS(PHTHALOCYANINATO) NEODYMIUM(III)

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**Abstract** Partial oxidation of hydrogen  
bis(phthalocyaninato) neodymium(III) by molecular  
iodine dramatically increases electrical  
conductivity. The results are discussed in terms of  
structural models.

INTRODUCTION

*Subscription*

Iodination of metallomacrocycles has been shown to be an effective synthetic approach to low-dimensional conducting materials consisting of partially oxidized molecular stacks.<sup>P</sup> The weakness of this approach is that there is little synthetic control over the the small differences in molecular and lattice forces which control the formation of stacks. An improvement to this approach was provided by the ("face-to-face" orientation of macrocycles found in the [M(Pc)O]<sub>n</sub> materials.<sup>e</sup> In this paper we show that a similar orientational effect exists in the linear chain compound

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composed of stacked hydrogen bis(phthalocyaninato) neodymium(III) [bis(Pc)Nd(III)] sandwich molecules.

### EXPERIMENTAL

Bis(Pc)Nd(III) was prepared and purified using previously described methods.<sup>3</sup> Partial oxidation of bis(Pc)Nd(III) was carried out with molecular iodine to obtain molecular compositions of bis(Pc)Nd(III)I<sub>y</sub> with y = 1.3 and 1.8. All materials were air stable during the period of the measurements. A pressure of 10<sup>7</sup> Pa was used to compress the materials into pellets 5 mm in diameter and typically 0.5 - 1.0 mm thick. The van der Pauw technique<sup>4</sup> utilizing four probe conductivity measurements was used. The probes were attached to the pellets using silver paste contacts. Room temperature resistivity values were measured for several days to check for any chemical reaction at the electrodes; none was observed. After high temperature measurements (>300 K), room temperature resistivity was checked again to ascertain whether decomposition had occurred; none was observed. Several runs were made on each sample to demonstrate reproducibility. All possible permutations of the voltage and current leads around the four probe network were examined at high and low temperatures to assure legitimate use of the van der Pauw theorem. A typical D. C. current of 10<sup>-5</sup> amps was used for variable temperature data sets. Ohmic behavior was observed for all samples.

### RESULTS

Variable temperature resistivity data shown in Figure 1

# ELECTRICAL CONDUCTIVITY OF $\text{Bis}(\text{Pc})\text{Nd}(\text{III})(\text{I}_3)_x$

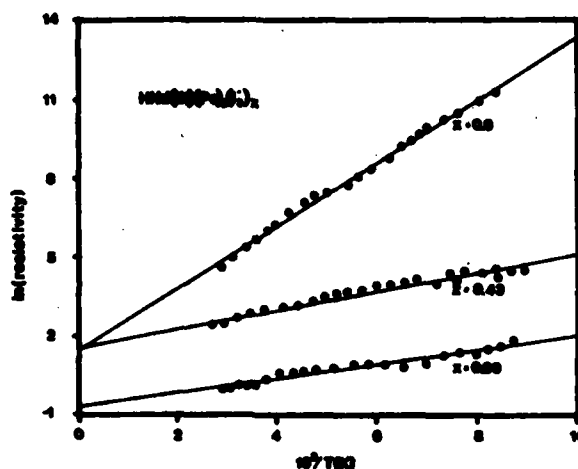


Figure 1. Electrical resistivity data for the series  $\text{bis}(\text{Pc})\text{Nd}(\text{III})(\text{I}_3)_x$ , with best fit lines.

indicate the polycrystalline samples to be thermally activated semiconductors. The data were fit by least-squares techniques to the thermally activated transport model

$$\sigma = \sigma_0 \exp(-\Delta/kT) \quad (1)$$

where  $\sigma_0$  is the infinite temperature conductivity and  $\Delta$  is the apparent activation energy. The parameters which describe each of the samples are set out in Table I. The data for  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$  are in agreement with previously determined data<sup>5</sup> (in ambient hydrogen and in air) which had revealed that absorbed oxygen decreased the resistivity values and the activation energies. Exposure of the iodinated complexes to oxygen was not expected to alter the

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TABLE I Electrical conductivity parameters for the series  $\text{bis}(\text{Pc})\text{Nd}(\text{III})\text{I}_y$ .

y	$\sigma_o (\Omega^{-1} \text{cm}^{-1})$	$\sigma_{RT} (\Omega^{-1} \text{cm}^{-1})$	$\Delta$ (eV)
0.0(air)	0.24	$4.5 \times 10^{-3}$	0.103
1.3	0.21	$6.4 \times 10^{-2}$	0.030
1.8	1.95	$0.8 \times 10^{-1}$	0.023

conductivity data since further oxidation was unlikely. Partial oxidation of  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$  by iodine dramatically reduces the resistivity and activation energy, as has been observed in the case of other metallomacrocycles.

#### DISCUSSION

The molecular structure of  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$  has been determined to be that of a sandwich compound<sup>6</sup> as opposed to the planar  $\text{M}(\text{Pc})$  units found for first row transition metal compounds. The neodymium ion occupies an eight coordinate central position between two parallel but staggered ( $45^\circ$ ) phthalocyanine molecules (Figure 2). The eight neodymium-nitrogen bonds range from 2.39 to 2.49 Å. These molecular units pack into the crystal as a chain which has a herring bone motif. Location of the acidic hydrogen in the complex has been very elusive in terms of experimental verification. Nichol森, et. al.,<sup>7</sup> proposed that the proton was firmly bound to only one of the phthalocyanine rings. To account for spectroscopic properties, Moskalev,



## ELECTRICAL CONDUCTIVITY OF $\text{bis}(\text{Pc})\text{Nd}(\text{III})(\text{I}_3)_x$

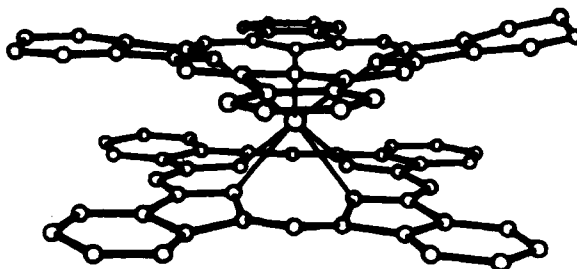


Figure 2. Sandwich structure of  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$ .

et. al.,<sup>8</sup> suggested that the proton bridges  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$  units in solution to form  $\mu\text{-H}$  dimers, trimers, etc.. Electrochemical studies<sup>9</sup> of solutions have shown that lanthanide sandwich compounds of the type discussed here show electrochromic properties which can be related to the oxidation state of the phthalocyanine rings. Hence, the presence of the acidic proton is of considerable importance in the redox properties of these systems. X-ray photoelectron spectra<sup>6</sup> have shown that the eight nitrogens are chemically equivalent. These documented experiments lead to the conclusion that the proton is located between the  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$  units in the solid state. Since the packing of the molecular units is similar to that of the  $\beta$  form of  $\text{CuPc}$ , this results in a "hydrogen bonding" bridged chain (Figure 3) qualitatively similar to the oxo-bridged  $\text{M}(\text{Pc})\text{O}$  polymers.

In hydrogen atmosphere,  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$  exhibits an activation energy that is 25% of that of  $\text{CuPc}$  and a room temperature resistivity that is four orders of magnitude smaller than that of  $\text{CuPc}$ . Measurements on  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$

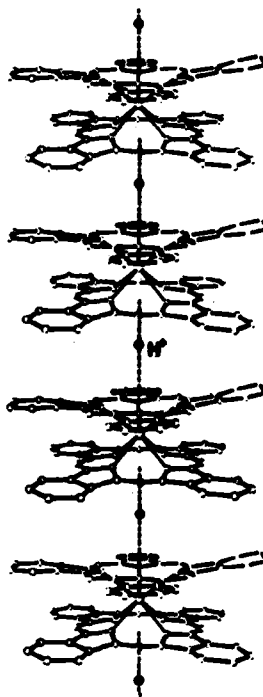


Figure 3. Hydrogen bonded molecules in bis(Pc)Nd(III) forming a linear chain structure.

exposed to ambient air, reveal decreased resistivity and activation energy relative to the same sample kept in a hydrogen atmosphere, presumably because of absorbed oxygen. The electrical conductivity values and activation energies for bis(Pc)Nd(III) are comparable to those of the Si(Pc)O polymer,<sup>2</sup> and bis(Pc)Nd(III) is a significantly better conductor than other M(Pc) systems. This can be understood in terms of the intermolecular hydrogen bond which promotes charge carrier transfer in a manner similar to that of the oxygen in the Si(Pc)O polymer. The presence of the acidic proton serves to bind the bis(Pc)Nd(III) units more tightly together resulting in shorter intermolecular contacts than

#### ELECTRICAL CONDUCTIVITY OF $\text{Bis}(\text{Pc})\text{Nd}(\text{III})(\text{I}_3)_x$

those usually observed in  $\text{M}(\text{Pc})$  systems. Hence, the increased conductivity and lowered activation energy can be understood in terms of the decreased distance between molecules and the consequential enhanced motion of the charge carriers.

The charge carriers in  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$  are mobile within the molecular units, and so we conclude that the conductivity of the system can be improved if the sandwiches are brought closer together. The effect of absorbed oxygen indicates that partial oxidation of the stacks increases the conductivity. Controlled oxidation of  $\text{bis}(\text{Pc})\text{Nd}(\text{III})$  by iodine verifies that this model is plausible. Furthermore, on a simple electrostatic basis, it may be seen that the molecular sandwich units repel each other less when they have been partially oxidized. As a consequence, the distance between sandwich units decreases, the interaction between them increases, and a decreased activation energy and improved charge carrier transport results.  $\text{Bis}(\text{Pc})\text{Nd}(\text{III})\text{I}_{1.3}$  has nearly the same infinite temperature conductivity as the unoxidized material, but only a slightly larger activation energy than the  $y = 1.8$  material. The  $y = 1.8$  material has the smallest activation energy, and its infinite temperature conductivity is larger than in the other two samples. These results indicate that the first oxidation level ( $y = 1.3$ ) decreases the activation energy nearly to the minimum value possible in this structure, while oxidation to the  $y = 1.8$  level only affects the number and the characteristics of the charge carriers.

It is well known that single crystal conductivities of low dimensional materials are usually two to three orders

of magnitude larger in the molecular stacking direction than in the pressed pellets of the same material. This is simply a consequence of the averaging of the crystallographic directions and interparticle resistance effects. Metallic conductivity behavior in the chain direction can be masked in the powder data due to the insulating behavior perpendicular to the stacking direction. One should compare  $\text{bis}(\text{Pc})\text{Nd}(\text{III})\text{I}_y$  powder data to that of a pressed pellet of the molecular metal  $\text{Ni}(\text{Pc})\text{I}_{1.0}$ ,<sup>10</sup> which has  $\sigma_{\text{RT}} = 7 \times 10^{-1} \Omega^{-1} \text{cm}^{-1}$  and  $\Delta = 0.04$  eV. However, single crystal room temperature conductivities along the stacking direction of  $\text{Ni}(\text{Pc})\text{I}_{1.0}$  are on the order of  $6 \times 10^2 \Omega^{-1} \text{cm}^{-1}$  and are metallic according to variable temperature data. This suggests that the conductivity of the  $\text{bis}(\text{Pc})\text{Nd}(\text{III})\text{I}_y$  materials may very well be metallic in the chain direction, thus stimulating continued efforts to obtain single crystals. This research was supported in part by the Office of Naval Research.

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